Next Generation Scalable Spaceborne GNSS Science Receiver

Jeffrey Y. Tien, Brian Bachman Okihiro, Stephan X. Esterhuizen, Garth W. Franklin, Thomas K. Meehan, Timothy N. Munson, David E. Robison, Dmitry Turbiner, Lawrence E. Young
Jet Propulsion Laboratory
California Institute of Technology

BIOGRAPHY (IES)

Jeff Tien is the task manager of the TriG GNSS receiver development. He received his MSEE degree from USC in 1994 and BSEE degree from Cal Poly, Pomona in 1990. Jeff has over 20 years of experience with both ground and space GPS receivers and high precision spacecraft positioning systems development. Jeff was one of the lead designers of the flight TurboRogue and BlackJack class of GPS receivers that have been successfully flown on over 14 space missions. More recently, Jeff has served as the manager of the Gravity Recovery Processor Assembly for NASA's GRAIL mission.

Brian Bachman Okihiro is currently an Electronics Engineer with the Advanced Radiometric and Gravity Sensing Instruments Group at the Jet Propulsion Laboratory. Started with the GPS Systems Group at JPL in 2007. Graduated with a Bachelor of Science in Electrical Engineering from California State Polytechnic University, Pomona, in 2009.

Stephan X. Esterhuizen completed his Masters degree in Electrical Engineering at the University of Colorado, Boulder in 2006. He received his B.S. in Electrical and Computer Engineering from the University of Colorado, Boulder in 2004. He joined JPL in 2006 where his primary task has been software and hardware development for precision ranging instruments.

Garth Franklin is the group supervisor for the Advanced Radiometric Instruments and Gravity Sensing Group at NASA's Jet Propulsion Laboratory. He received his BS from Cal Poly Pomona in 1992. His group designs, builds and flies high precision GPS receivers for scientific applications and precise orbit determination of low earth orbiters including Jason (I, II & III), Champ, Sac-C, GRACE and GRAIL. They are currently focused on the next generation of GNSS radio occultation science instrument ('TriG') that will enable atmospheric profiles in large quantities down to the surface of the earth. For the past few years, Mr. Franklin has also been the I&T manager for the Lisa Pathfinder mission.

Tom Meehan is a Principal Member of the Technical Staff at JPL. He has worked on high precision GPS design and development at JPL since 1987 and led three major GPS instrument developments at JPL. He was the Co-investigator for the GPS/Met occultation receiver on the MicroLab spacecraft and led the development of NASA's BlackJack spaceborne GPS receiver. Mr. Meehan holds several U.S. patents for GNSS signal processing and is currently doing instrument design and algorithm development for radio occultations, ocean reflections and digital beam forming of GNSS signals. He is currently working with the SAC-C and COSMIC spacecraft to devise improved algorithms for GPS-based occultations and reflections and works as one of the principal designers of the TriG, GNSS space receiver.

Timothy Munson is a member of the Global Positioning Satellite Systems group at the Jet Propulsion Laboratory. He has more than 25 years of experience in GNSS Systems Engineering and GPS receiver design and operations for both ground and space receivers. He has specialized in Software Defined Radios in space environments.

David Robison holds a BS and MEng in Electrical Engineering and Computer Science from MIT, and has worked in the Advanced Radiometric and Gravity-Sensing Instruments group at JPL since 2001. He has served as the Cognizant Engineer for GPS Receiver instruments on COSMIC, OSTM, and UAV-SAR. His varied contributions include the in-flight firmware upgrade that enabled L2 Civil tracking on CHAMP and COSMIC, as well as the data processing firmware for the Moon Mineralogy Mapper. He is currently responsible for signal processing firmware design for the TriG GNSS Receiver and the CoNNeCT GPS Waveform.

Dmitry Turbiner got his BS in Electrical Engineering at MIT in 2010 and has been in the GPS Systems group at

JPL since. His primary focus has been on RF and Antenna design for the next generation GNSS space receiver.

Dr. Larry E. Young earned a B.A. (Physics) from the Johns Hopkins University in 1970 and a Ph.D. (Nuclear Physics) from the State University of New York at Stony Brook in 1975. Larry has developed radiometric systems at Caltech's Jet Propulsion Laboratory since 1978, and currently supervises a group developing high precision GPS measurement systems for remote sensing from space.

ABSTRACT

Several upcoming NASA and NOAA missions require an advanced science-quality GNSS receiver as a mission-critical payload for cm-level precise orbit determination and/or Radio Occultation (RO) observations to meet their science objectives. The science and navigation requirements dictate that GNSS receivers track signals from GPS, GLONASS, and other GNSS systems as they become available.

JPL is developing the next generation GNSS receiver for flight called the TriG Receiver enabling continued access of precision orbit determination for remote sensing missions and the application of GNSS signals for the technically demanding RO and surface reflections observations. Derived from the NASA/JPL BlackJack receiver design, which has flown on over 16 spacecraft with over 115 years of successful operations, the TriG offers significantly enhanced capability to track more GNSS signals with higher SNR. The TriG receiver will track both the legacy and new signals from GPS as well as new GNSS signals from Galileo and GLONASS. The ability to track multiple GNSS satellite signals will improve both precision orbit determination and the quality and quantity of the RO measurements.

The TriG receiver features several innovations including digital beam steering to produce multiple simultaneous high-gain beams, wideband open loop tracking, and an advanced "time delayed" signal processing algorithm. These innovations improve precision for RO in the upper atmosphere while also supporting the wider range in delay and Doppler shift necessary for full RO retrieval in the lower troposphere. The TriG receiver is implemented in scalable 3U architecture and is fully reconfigurable enabling optimization to meet specific mission requirements and spacecraft resource constraints.

This paper will describe the TriG architecture, and how the new features will benefit the next-generation of global network instruments, as well as current test results.

INTRODUCTION

The Global Navigation Satellite Systems (GNSS) provide Positioning, Navigation, and Timing fundamental to nearly all NASA Remote Sensing missions [1]. NASA's BlackJack and TurboRogue receivers have been used on more than 10 missions including SRTM, CHAMP, SAC-C, JASON, GRACE, COSMIC and others, for Earth surface change characterization, high resolution gravity, topography, and autonomous operation.

In addition, GNSS-RO technology, pioneered with NASA technology using the TurboRogue and BlackJack GPS receivers on various missions including GPSMET, CHAMP, SAC-C, and COSMIC [2][3], has been demonstrated to be a low cost and effective technology to provide global Earth observations including refractivity, temperature, moisture, and electron content profiles of the troposphere, stratosphere, and ionosphere including scintillation (Figure 1).

2007 NRC Decadal Survey for Earth Science [4] recommends:
"NASA should implement a set of 15 missions phased over the next decade. All of the appropriate low Earth orbit (LEO) missions should include a Global Positioning System (GPS) receiver to augment operational measurements of temperature and water vapor."

"In view of the importance of the occultation measurement and the accurate positioning of the satellite for other sensor measurements, GPS receivers should be a standard part of both NASA and NPOESS low-Earth-orbit payloads."

The receivers envisioned in the Survey are described as:
"The payloads would be advanced RO receivers that could receive GPS, GLONASS, and Galileo radio signals."

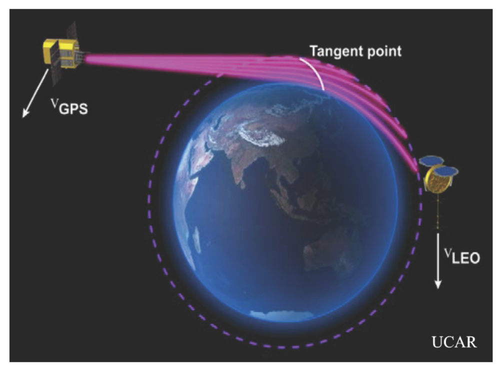

Figure 1. A pictorial illustration of a GNSS Radio Occultation receiver on a low earth-orbiting platform tracking signal from a GPS satellite.

More recently, GNSS reflection (Figure 2) is becoming an emerging technology to monitor local sea level variations caused by currents and oceanic gyres, tsunami detection, sea surface roughness, and soil moisture [5][6][7][8].

Figure 2. A pictorial illustration of a TriG GNSS reflection instrument on an Earth orbiting platform. Direct signals for navigation are received by an upward viewing antenna. The weak GPS reflected signals are received with a downward looking high-gain steerable antenna array.

JPL is developing the next generation scalable GNSS receiver for flight in collaboration with Broad Reach Engineering. The TriG Receiver will provide precision orbit determination for remote sensing missions using a variety of new GNSS signals, and will greatly improve the availability and precision of RO and surface reflection surface reflections observations using its multi-beam phased array antenna combined with innovative near real-time tracking algorithms.

Derived from the NASA/JPL BlackJack receiver heritage, which has flown on over 16 spacecraft with over 115 receiver-years on-orbit of successful operations, the TriG offers significantly enhanced capability to track more GNSS signals with higher SNR. The TriG receiver will be capable of tracking both the legacy and new signals from GPS, GNSS signals from Galileo, GLONASS, Compass and others, and signals from other navigation systems such as DORIS.

The ability to track multiple GNSS satellite signals will improve both precision orbit determination and the quality and quantity of measurements from RO and surface reflection observations.

KEY FEATURES

- Scalable 3U architecture accommodates up to 16 multi-frequency antenna inputs.
- Receives all L band GNSS signals including GPS, Galileo, GLONASS, and Compass, as well as UHF/S band DORIS signal.
- Multiple digitally steered high-gain beams.
- Large software reconfigurable digital signal processing resource with up to 300 GNSS signal processing channels
- On board dynamic power management.
- Advanced signal processing including open-loop tracking, and time-delay signal processing.
- Allow either internal or external frequency reference.
- Highly reliable design with for Total Ionized Dose (TID) > 40krad
- Autonomous Operations
- Data uses "total observable". Observable formation algorithms are freely available to users.
- Design allows easy modification of onboard processing by non-receiver experts

SCALABLE 3U ARCHITECTURE

The TriG receiver is implemented in a scalable 3U architecture ranging from a one to four antenna single-processor configuration (Figure 3) suitable for POD applications to an eight to sixteen antenna dual-processor configuration as shown in Figure 4 for the technically demanding RO and surface reflection applications. The TriG receiver is fully software and firmware reconfigurable enabling optimization to meet specific mission requirements and spacecraft resource constraints.

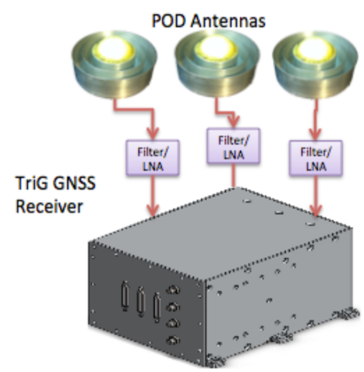

Figure 3. TriG GNSS Science Receiver in three antennas single processor configuration.

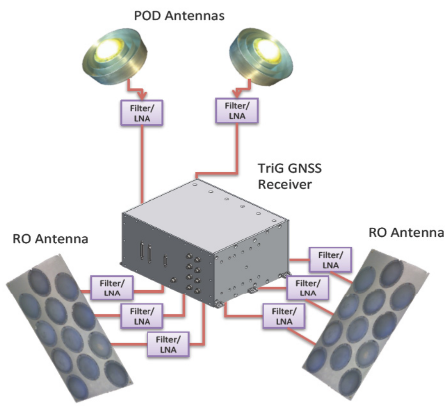

Figure 4. TriG GNSS Science Receiver in eight antennas dual processor configuration.

RECEIVE ALL APPROPRIATE GNSS SIGNALS

GPS is in the process of modernizing the entire system of ground control infrastructure, satellites, and signals and deploying a new system called GPS III over the next 10 years and in the process will retire the Y code in 2020 from civil use. This code will be replaced at L2 with a higher SNR code called L2C [9], and the new L1C code will provide a civil replacement for the L1 Y code.

The GPS constellation started to broadcast at the L5 frequency on April 10, 2009. Decadal Survey RO, POD, and some ionospheric calibration applications require L5 tracking. L5 capability is required to track the European Galileo system, which will transmit the E5A signal at the same frequency as GPS L5. The Russian GLONASS now transmits Frequency Division Multiple Access (FDMA) signals near L1 and L2, and will add CDMA signals in the next few years, which will make GLONASS more attractive for occultation and other precise applications. Additionally, the Chinese Compass GNSS Constellation is becoming available with the recent publication of the draft ICD.

The TriG receiver will be capable of tracking both the legacy and new signals from GPS to provide uninterrupted multi-frequency GPS tracking service through 2020, as well as other GNSS signals from Galileo, GLONASS, Compass, and others. TriG is very flexible, and is capable of using the DORIS ground-based navigation system.

The ability to track multiple GNSS satellite signals will improve both precision orbit determination and the quality and quantity of the measurements from RO and surface reflection observations.

DIGITAL BEAM STEERING

TRIG is designed to track up to 16 antenna inputs, each with up to four frequency channels, which can be phased and digitally combined to produce multiple beams with high-gain for all receive frequencies, which will improve both low and high altitude occultation performance as well as the ability to acquire synoptic surface reflections data over a wide swath of ocean or solid earth [10].

Digital beam steering is a technique wherein the signals from an array of several antenna elements are digitally sampled and then combined to focus the antenna gain in a set of preferred directions [11][12]. Digital Beam Steering allows a group of antenna elements to act as a set of high gain directional antennas with the capability to observe in many directions at once. It also reduces multipath and RFI susceptibility by providing reduced gain toward the sources of multipath and RFI.

FULLY SOFTWARE RECONFIGURABLE

The TriG receiver is implemented in dual processor scalable 3U architecture that is fully software reconfigurable, which would permit changes be made to the onboard software and firmware to improve data quality, track new signals, and enable new experiments post launch.

The TriG receiver dual processors have more than 6 times the throughput and more than 6 times the reconfigurable logic gates for digital processing than what was implemented in the BlackJack/IGOR GPS receiver, which provide the TriG with up to 300 satellite signal processing channels. This enables the TriG to track 24 multiple frequency satellites for POD and ionosphere estimation, plus 8 satellites for occultation with digital beam steering. This level of capability will allow TriG to take advantage of all foreseeable GNSS signals.

The TriG receiver will have separate processor boards, one for the POD and a separate Science processor based on Linux operating system for occultation, reflection and new applications. The Linux based Science processor board would allowing signal processing algorithms developed with standard Desktop Linux to be easily ported to the TriG Science processor, thus significantly reduces the development time. Significantly, this also diminishes the need for experts in the receiver onboard software for continued software development.

The TriG receiver also features an onboard power management scheme exploiting the processor on-chip power management to efficiently enable/disable resources, including RF channels, on demand to minimize power consumptions based on real-time tracking needs and power constraints.

ADVANCED SIGNAL PROCESSING

The TriG receiver implements large memory buffer and reconfigurable digital logic to enable the implementation of the "blueshift" algorithm, which allows the GNSS receiver to track under low SNR conditions such as are encountered in the lowest 2 km of the atmosphere. It accomplishes this by running multiple correlations with varying lags and with multiple models. This is one of the major prongs of the strategy to track the occultation signal all the way to the ground. Blueshift is also needed to raise the yield from rising occultations, where atmospheric model errors are challenging.

Multi-Lag Processing: Measuring the power for each GPS signal with many (tens or hundreds) lags is not available with any flight GPS receiver. For atmospheric occultation processing, multi-lag correlators allow use of a wider spread of range and Doppler models so that rising signals can be reliably captured. Currently, 20-30% of rising occultations from the BlackJack GPS receivers are discarded due to inaccurate modeling. In the case of surface reflections, the signals of interest may be spread over many delay channels.

Time Delayed Processing: After processing by the RF front end, each digital data stream is routed by FPGA logic into a high-speed memory buffer. Buffering the data in this way allows occultation data to be processed "offline", but keeping up with realtime, allowing time for the POD processor to send more accurate models of SC geometry and oscillator behavior to the occultation processor. The occultation processor generates third order range models to extract the best phase and amplitude solution for each occultation. This maximizes the number of recoverable occultation profiles. For example, when attempting to track a rising satellite, the *a priori* atmospheric model has a very large influence on the ability of the receiver to lock onto the signal and track it in the lower troposphere. TriG data quality checks can assess poor RO signal recovery and re-process the data on board. So, if the *a priori* atmospheric model that is tried results in a failed rising occultation, re-processing with alternate models or even with time-reversed data can be employed to maximize the number of successful RO profiles.

The previous processing scenario is just one of many available with the TRIG architecture. By allowing for some latency for the data products, the software can examine the reflection data while holding the raw digitized bit streams for a subsequent reprocessing step if desired. An added benefit from the "time-delayed" processing approach is the Doppler and range models are likely to be more accurate since extrapolation of the navigation position and clock solutions to future times isn't necessary.

FREQUENCY REFERENCE

The TriG receiver accommodates a built-in Ovenized Oscillator (OCXO) with 1-sec stability of 2E-12, and also an input to use external USOs. USOs are required for zero differenced radio occultation as desired for SI traceability, and as needed for high precision gravity mission needs such as the GRACE follow-on missions.

RELIABILITY

Several upcoming NASA missions require receivers with higher reliability because the GPS receivers are being used for mission critical POD. Radiation related outages add unnecessary risk to the mission. It is cost effective to design the new receiver to meet the higher reliability standards and have one receiver that can service multiple missions rather than try to upgrade a receiver with new parts to meet the higher standard.

The TriG receiver offers greater reliability compare to the previous generation BlackJack/IGOR GPS receiver by using all high-rel space grade parts with radiation tolerance of more than 40krad and Single Event Latchup threshold of greater than 60 LET.

Triple Module Redundancy (TMR), Error Detection and Correction (EDAC), and configuration memory scrubbing are also implemented to minimize the impact of SEUs.

AUTONOMOUS OPERATION

TRIG is designed to be an autonomous science-instrument requiring no special initialization sequence or detailed observation scheduling. This approach is modeled after that of the BlackJack GPS space receiver, which needs no configuration commands to acquire GNSS satellites, solve for position, and begin science observations of radio occultations or surface reflection.

Once the GNSS receiver has successfully produced a navigation solution, the Reconfigurable Digital Processor (RDP) is time-synchronized to the GNSS (effectively UTC). This synchronization is set to within one reference clock cycle (~50 ns) by the FPGA logic in the RDP. When a science observation is scheduled, the Science Processor performs the following tasks:

- Schedules Iono/Atmo Occ Profiles
- Extracts high-rate phase/range/amp
- Formats and compresses science data
- Selects optimal reference satellites for differencing,

- Computes a real-time model of atmospheric bending along GPS ray-path for open-loop signal capture in the lower troposphere

TRIG SYSTEM ARCHITECTURE

MAJOR COMPONENTS

The TRIG receiver electronic design is based on the 3U architecture comprised of 4 main components:

- RF Downconverter (RFDC)
- GNSS Navigation Processor
- Science Processor
- Reconfigurable Digital Processor

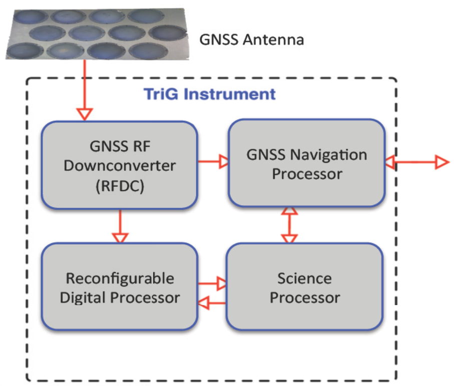

Figure 5. TriG GNSS receiver architecture diagram.

RF DOWNCONVERTER (RFDC)

The TriG wideband RF downconverter uses a programmable RFIC that has been radiation tested to > 60 krad. The RF downconverter receives inputs from the antenna array after passing through external wideband preselect filter and Low Noise Amplifier (LNA). The signal is then down-convert to baseband and digitized before it is send to the digital signal processors. Each of the RFICs has an internal programmable LO that is software configurable to receive signals from UHF, L Band, or S Band, which would allow the receiver to receive any of the L Band GNSS signals including GPS, GLONASS, Galileo as well as the signal at UHF/S band from DORIS transmitting stations.

The RFIC also has built-in programmable gain, and programmable baseband filter bandwidth to allowing efficient use of signal bandwidth to maximize SNR for specific applications. The built-in power off feature also allows software to power off RF channels when they are not in use to reduce power consumption.

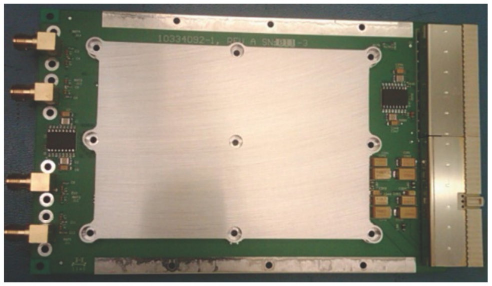

Figure 6. Wideband reconfigurable GNSS RFDC

GNSS NAVIGATION PROCESSOR

The TriG GNSS Navigation Processor is based on the BlackJack GPS receiver baseband processor with signal-processing algorithms that have successfully flown on more than 14 different Earth science missions. The GNSS Navigation Processor receives the sampled baseband signal from the RFDC, acquires and track the GNSS signals, generates real-time 8-state navigation solution, formats the data, and outputs predicts to the Science Processor. The TriG GNSS Navigation Processor is fully software configurable with large FPGA-based reprogrammable logic gates adequate for up to 100 individual signal-processing channels. A large memory buffer is also implemented in the GNSS real-time processor for “Blue-Shift” signal processing which doubles the processor throughput compare to the previous BlackJack implementation.

The TriG receiver with single GNSS Navigation Processor and RFDC would constitute the minimum configuration to support POD application.

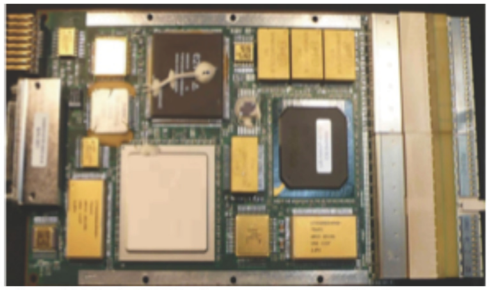

Figure 7. The TriG Navigation Processor Card.

SCIENCE PROCESSOR (SP)

The SP controls the digital signal processing of the Reconfigurable Digital Processor. It receives real-time navigation and timing data from the GNSS navigation processor and uses this to schedule science observations such as RO and reflection observations. The SP uses a Linux based computer, which simplifies the development and integration of the science application software to the TriG receiver. For each observation sequence, the SP sets up the observation start/stop time, writes signal-processing models to the RDP and reads back the correlation products. The command/data interface between the SP and RDP is through the dedicated DMA interface with data transfer rate of up to 100 MByte/sec.

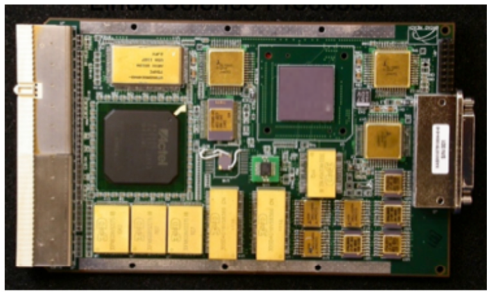

Figure 8. The Linux based TriG Science Processor Card.

RECONFIGURABLE DIGITAL PROCESSOR (RDP)

The TRIG Reconfigurable Digital Processor (RDP) received sampled data from the RFDC and performs high-speed phase counter rotation, multi-beam combining, correlation, accumulation, and data compression. The RDP has large programmable logic resources enough to accommodate up to 200 signal processing channel for RO. A large buffer memory is also implemented to allow time-shift processing, which allow the occultation data to be processed "offline" allowing time for the Navigation processor to send accurate models of SC geometry and oscillator behavior to the Science Processor. The operation of the TriG RDP is controlled by the Science Processor.

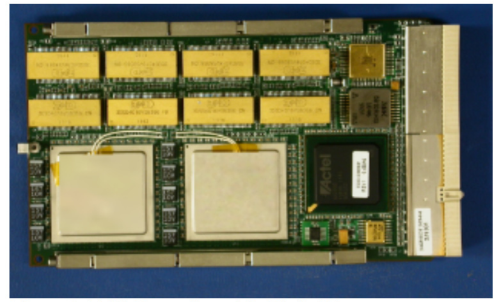

Figure 9. TriG Reconfigurable Digital Processor.

RECENT DEVELOPMENT STATUS

The TriG GNSS receiver Engineering Model (EM) has been developed and is currently undergoing unit test and system integration.

Both hardware functionality and interface of the Navigation Processor and Science Processor have been verified. The porting of the BlackJack software to the Navigation processor is nearly been completed. The Linux operating system has been ported to the Science Processor and benchmark performance testing is underway. The Reconfigurable Digital Processor has been fully assembled and unit test is currently underway.

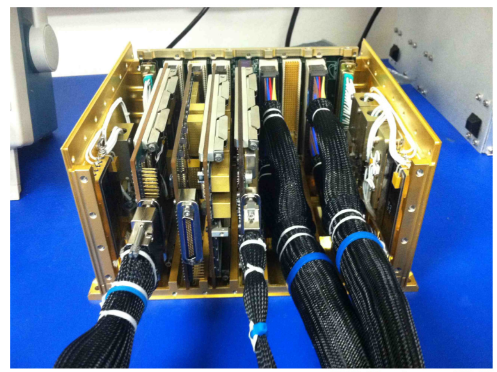

Figure 10. EM TriG GNSS Receiver 3U Hardware Unit Test

The RFDC has been developed and tested in a thermal chamber over temperature and compared to the performance of a BlackJack/IGOR receiver front-end. The SNR across all RF channel is within 0.5dB and comparable to the performance of BlackJack/IGOR receiver front-end.

Differential group delay (see Figure 11) varies less than 2 ns and differential phase delay (see Figure 12) varies less than 10ps over the temperature range of 0 to +40C, which are relevant parameters for the measurement of the absolute ionospheric TEC and of the TEC variation over a track.

Effort to integrate RO software for both GPS and GLONASS FDMA will start in early Spring 2012 and expects to be complete in late 2012.

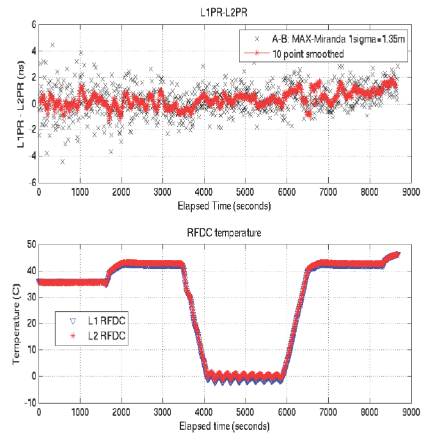

Figure 11. L1-L2 group delay variation of the TriG RFDC measured to less than 2 ns over temperature range from 0 to +40C.

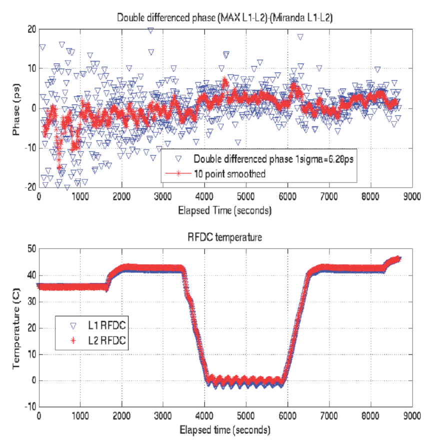

Figure 12. Double differenced L1-L2 phase variation of the TriG RFDC measured to less than 10 ps over temperature range from 0 to +40C.

POWER, MASS, DIMENSIONS

TriG GNSS receiver is scalable and the mass, power, and dimensions varies with configuration. Table 1 gives approximate specifications for power, mass, and dimension for four different TriG GNSS receiver configurations.

Table 1. TriG GNSS Receiver Power, Mass, Dimensions.

Configuration	**Power (W)**	**Mass (kg)**	**Dimension LxWxH (cm)**
Single Antenna/Single Processor	16 to 20	4	20 x 16 x 12
Four Antenna/Single Processor	18 to 25	4	20 x 16 x 12
Four Antenna/Dual Processor	30 to 50	5	20 x 20 x 12
Eight Antenna/Dual Processor	40 to 60	6	20 x 23 x 12

SUMMARY

JPL is developing the next generation scalable space borne TriG GNSS receiver capable to track legacy and modernized GPS signals as well as other GNSS signals including GLONASS, and Galileo. The TriG will enable Earth Science missions to have continued access to precision orbit determination for remote sensing missions and will exploit the new set of GNSS signals to produce RO and surface reflections observations of unprecedented quality.

The TriG receiver features many innovations including digital beam steering to produce multiple simultaneous high-gain beams, wideband open loop tracking, and advanced "time delayed" signal processing algorithms. The TriG receiver is implemented in scalable 3U architecture and is fully software reconfigurable enabling optimization to meet specific mission requirements and spacecraft resource constraints.

The TriG GNSS receiver Engineering Model (EM) is currently undergoing testing and is expected to complete full performance testing later this year.

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Special thanks to Broad Reach Engineering for the

improvements they made to the BlackJack design with their IGOR occultation instrument.

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